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Advanced Controls of Diesel Engines

N. A. Henein

Wayne State University

Abstract

Major developments in diesel engine technology enabled accurate control of the combustion process, to meet the stringent emissions standards, particularly for NO_x and particulate matter (PM). This led to the development of advanced combustion regimes to decrease NO_x and PM engine-out emissions and reduce the reliance on after-treatment devices. This work examines the effects of exhaust gas recirculation (EGR), injection pressure and swirl motion on engine-out emissions in the conventional and Low Temperature Combustion Regimes (LTC). Experiments were conducted on a single cylinder, 4-valve, direct injection diesel engine equipped with a common rail injection system. The pressure and temperature in the inlet and exhaust surge tanks were adjusted to simulate turbocharged diesel engine conditions. Engine-out emission measurements included hydrocarbons, carbon monoxide, smoke and NO_x. EGR rates were varied over a wide range to cover the engine operation from the conventional to the low temperature combustion regime, up to the misfiring point. The effects of different engine control parameters on the autoignition reactions, cool flames, and premixed and mixing controlled combustion fractions are examined. The trade off between NO_x and BSU are determined in 2-D and 3-D maps that show the iso-EGR lines and surfaces. The penalty in BSU, HC, CO and indicated specific fuel consumption (ISFC) were determined over the whole EGR range. A comparison between the use of higher injection parameters and higher swirl ratios to control engine-out emissions is made.

Background

Different combustion regimes, developed to reduce engine out emissions, include the smokeless lean combustion (MK) concept [1], the low temperature smokeless rich combustion [2] and the UNIBUS system [3] and modified low LTC [4]. These regimes require the control of the injection pressure, EGR, injection timing and swirl ratio. This work examines the effect of these controls on engine-out emissions in the conventional and the low temperature lean combustion regime, LTC.

Diesel Combustion: Conventional and LTC Regimes

Figure 1 shows the effect of increasing EGR on engine-out emissions over a wide range, till the engine misfired. This figure can be divided in three parts:

(a) Conventional diesel combustion where EGR was increased from 0% to 60% causing NO_x emissions to continuously drop, while BSU and CO increased at an accelerating rate at the high EGR rates. Slight changes are observed in HC and ISFC as EGR increased to 50%, after which incomplete combustion products appeared at a higher concentration, and ISFC increased.

(b) Low Temperature Combustion (LTC) where EGR increased from 60% to 64% EGR, causing BSU to drop sharply, while the already low NO_x dropped to fairly lower values. CO increased at a high rate and HC almost remained constant. The operation of the engine in this zone was unstable and the COV was lower than that in the conventional combustion regime.

(c) Unstable Operation and Misfiring Zone:

Any increase in EGR beyond 64% resulted in unstable engine operation due to large cycle-to-cycle variations and occasional misfiring.

Effect of EGR on Engine-out Emissions in the Conventional Diesel Combustion Regime

The increase in EGR has the following effects on the combustion process and engine out emissions in the conventional combustion regime:

1. It slowed down the auto ignition reactions as indicated by a 44% increase in ID at 60% EGR.
2. Increase in EGR enhanced the production of cool flames that remained for a longer period of time at the higher EGR rates. The long cool flame periods allowed more time for the liquid fuel evaporation and mix with the fresh charge.
3. EGR reduced the rate of the oxidation reactions during the whole combustion process due to the lower concentration of oxygen and lack of proper mixing with oxygen, in addition to the drop in temperature at the higher EGR rates. The reduction in the rate of burning occurred in spite of the increase in evaporation and mixing.
4. EGR increased the CO emissions in spite of the better mixing at the higher EGR rates, is caused mainly by the drop in the oxygen content of the charge. Other factors that might have contributed to the increase in CO at higher EGR are the increase in the fuel deposited on the walls and the poor oxidation reactions. At higher EGR rates, the longer ID and cool flame periods allow more time for the light components of the fuel to evaporate leaving the heavier components on the walls. As these heavier components evaporate late in the expansion stroke, their oxidation reactions suffer because of the low oxygen contents, in addition to the lower mass average temperature of the combustion products.

Effect of EGR on Engine-out Emissions in the LTC Regime

Increasing EGR from 60% to 64% caused a drop in both NO_x and BSU. A possible explanation for the drop in smoke at the highest EGR rate is given in a recent publication by Aceves 2005 [17]. The model predicted the chemical composition and concentration of soot precursors, which were considered good indicators of soot production in the engine. Aceves concluded that reducing the temperature and increasing the rate of mixing tend to reduce the production of the soot precursors. These findings can explain some of the trends observed in this investigation where the mixing was increased during the long ignition delays and the temperatures were reduced at the very high EGR rates in the LTC regime. But the cause of the sudden change in soot emissions by an increase of one or two percent in EGR cannot be explained.

Effect of swirl ratio in the conventional diesel combustion at Zero EGR

Figure 3 shows that ISNO_x emissions increased by about 50% as the SR increased from 1.44 to 7.12. This is mainly caused by the following; (1) Better fuel evaporation and mixing with the fresh charge, due to (a) the higher relative velocity and its effect on increasing the heat and mass transfer coefficients between the liquid phase and gas phase, (b) the spread of the spray over a wider angle [5], and the increase in the lean flame region down stream the swirl motion [6] and (c) the increase in the wetted surface area of the wall after the spray impinges on the wall. All these factors contribute to the increase in the volume of the premixed charge. (2) Higher swirl ratios increase turbulence and mixing and enhance the reaction rate, as evident from a 40% increase in the rate of heat release from premixed combustion fraction. This increase occurred, in spite of the increase in the cooling losses at the higher SR. The analysis shows the increase in the swirl ratio from 1.44 to 7.12 caused a drop of 2 bar in compression pressure and about 80 °C in the compression temperature.

Effect of swirl ratio on Engine-out Emissions in the Conventional Diesel Combustion at 60%EGR

The effect of swirl at 60% EGR is significantly different than its effect at 0% EGR. The increase in SR from 1.44 to 4.94 reduced BSU sharply. This can be attributed to the better mixing. But a further increase in swirl ratio from 4.94 to 7.12 caused an increase in both the BSU and CO, which can be attributed to the drop in the charge temperature caused by the higher cooling losses, possible overlapping of the adjacent

sprays creating a rich mixture, and the change in the gas dynamics caused by the interaction between the squish and swirl components.

The penalty in fuel economy caused by the high SR increased at the 60% EGR, because of the longer period and late fuel burning.

Effect of Injection Pressure on Engine-out Emissions in the Conventional and LTC Regimes

Figure 5 shows that the increase in injection pressure is very effective in reducing BSU, at all the EGR ratios in both the conventional and LTC regimes. It is interesting to notice the drop in NO_x at the higher injection pressures in the LTC regime.

Comparison Between the Effects of Injection Pressure and Swirl Ratio on the Trade Off Between NO_x and BSU Emissions in the Conventional Diesel Combustion and LTC Regimes

Figure (6) shows a comparison between the effects of injection pressure and swirl ratios on the trade-off between NO_x and BSU in the conventional diesel and LTC regimes. Increasing the injection pressure by a factor of 2, from 600 bar to 1200 bar, reduced BSU by 80%. Meanwhile, increasing the swirl ratio from 1.44 to 2.59 reduced BSU by a factor of 66% in LTC regime. However increasing swirl by a factor of ~5 (1.44 to 7.12) reduced BSU by a factor of only 33% in the LTC regime. Increase of Injection pressure to 1200 increased fuel consumption by about 10% in both conventional and LTC combustion regimes. However these data does not reflect the additional energy required for driving the high pressure pump. Increase of swirl ratio from 1.44 to 7.12 increased fuel consumption by about 20% in both the regimes.

Conclusions

1. The major difference between the conventional and LTC regimes is in the % EGR applied to the fresh charge. Increasing EGR reduces NO_x continuously in both regimes. However, increasing EGR increases engine-out soot emissions in the conventional diesel combustion, to a point where it peaks. Any further increase in EGR brings the engine in the LTC regime where any increase in EGR reduces soot to a level still higher than that at 0% EGR. This has been observed at all the injection pressures in this investigation.
2. The LTC regime requires very accurate controls since combustion is very sensitive to small variations in EGR. The high EGR required for LTC is very close to the misfiring EGR limit.
3. Soot, at the high EGR rates in the two regimes, can be reduced by applying high injection pressures and a moderate swirl ratio. There is an optimum SR beyond which any increase results in a penalty in BSU.
4. There is a penalty in fuel economy and a fairly high increase in CO at the higher EGR rates particularly in the LTC regime.
5. The penalties reported in this investigation do not reflect the additional energy required to drive the fuel pump at the high injection pressures, the increase in the cooling losses and drop in the volumetric efficiency at the high swirl ratios.

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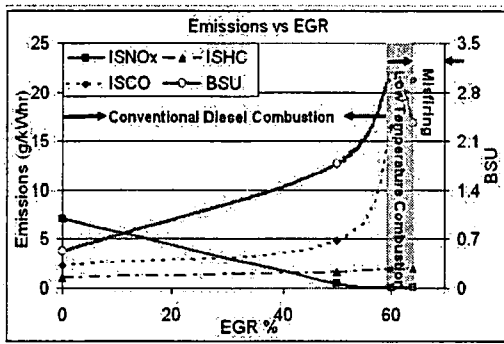


Figure 1. Effect of EGR on engine-out emissions in the conventional and LTC regimes.

[Pinj= 600 bar, EGR= variable, LPPC= 05aTDC, Swirl Ratio= 1.44 for all]

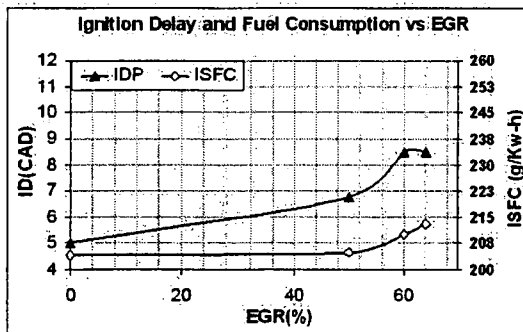


Figure 2. Effect of EGR on engine-out emissions in the conventional and LTC regimes.

[Pinj= 600 bar, EGR= variable, LPPC= 05aTDC, Swirl = 1.44]

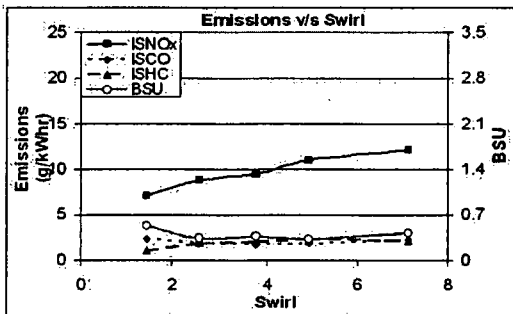


Figure3. Effect of swirl Ratio on engine-out emissions in conventional zone.

[Pinj= 600bar, EGR= 0%, LPPC= 05aTDC, Swirl Ratio = 1.44-7.12 for all]

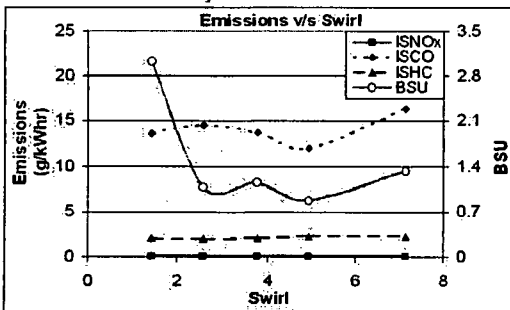


Figure 4: Emissions versus Swirl in LTC Regime.

[Pinj= 600bar, EGR= 0%, LPPC= 05aTDC, Swirl= 1.44-7.12]

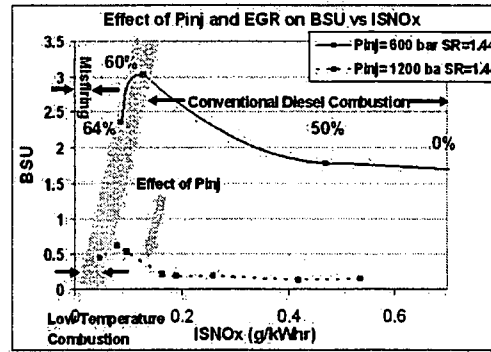


Figure 5. Trade-Off between NOx and BSU at different injection pressures in the conventional and LTC Regimes

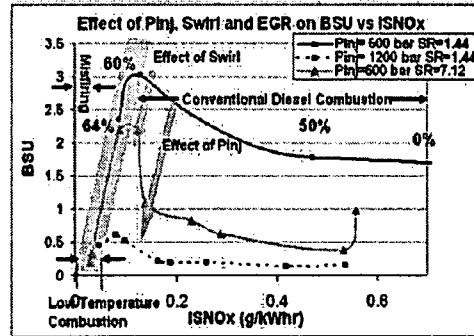


Figure 6. Trade-Off Between NOx and BSU at different injection pressures, EGR and Swirl Ratios in the conventional and LTC Regimes.